Explore sustainable European futures

Carbon Capture, Use and Sequestration module

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Short Description
The CCUS module provides a detailed analysis of the CCUS process by breaking down the carbon flow from capture (CC), sequestration (CCS) and utilization (CCU). *This report describes the Carbon Capture, Utilization and Sequestration (CCUS) module, and in particular:* - *The sources and hypotheses used to generate the input data;* - *The calculation logic and scope of the module;* - *The lever choices and ambition levels.*

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This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

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List of abbreviations

BECC: Bio-energy carbon capture

BF: Blast furnace

BOF: Basic oxygen furnace

CAPEX: Capital expenditure

CC: Carbon capture

CCS: Carbon capture and sequestration

CCU: Carbon capture and utilization

CCUS: Carbon capture utilization and sequestration

DAC: Direct air capture

DMC: Dimethyl carbonate

DME: Dimethyl ether

DSM: Demand side management

DOGR: Depleted oil and gas reservoirs

DOI: Deep ocean injection

DRI: Direct reduced iron

DSF: Deep saline formations

EAF: Electric arc furnace

EOR: Enhanced oil recovery

GHG: Greenhouse gas

GWP: Global warming potential

IPCC: Intergovernmental panel on the climate change

IGCC: integrated gasification combined cycle

IPS: Industry and power sectors

LCA: Life Cycle Assessment

LHV: Lower heating value

MEA: Monoethanolamine

MOF: Metal organic framework

MS: Mineral storage

MTPA: Million tons per annum

NGCC: Natural gas combined cycle

OPEX: Operating expenses

UCS: Unmineable coal seams

PSA: Pressure swing adsorption

PtG: Power to Gas

PV: Photovoltaic

TRL: Technology readiness level

UNFCCC: United nations framework convention on climate change

WP: Work Package

Introduction

Decarbonization is becoming an essential and urgent issue in human activities, infiltrating into various societal fields, including climate, politics, culture, economy, environment, lifestyle, ecology, resource and so on. In the context of striving for a sustainable society, participating countries in the Paris Climate Summit reached an agreement within the UNFCCC, declaring the objective of keeping the increase in global average temperature below 2°C above pre-industrial levels within this century; and further to pursue efforts to limit the increase to 1.5°C. Europe has a pioneering role in exploring plausible pathways towards this long-term objective, and has to revolutionize the current situation, in particular in energy supply, mobility and industry sectors. To realize this target, two approaches are generally considered:

1. Mitigating the carbon sources: for instance, by increasing the penetration of renewable energy technologies in its electricity mix, by promoting the development of soft mobility or electric vehicles or by improving energy efficiency in buildings;
2. Reinforcing the carbon sinks: applying Carbon Capture, Utilization and Sequestration (CCUS) technologies and promoting afforestation/ reforestation measures.

In the EUCalc project, the mitigation options are implemented in the Lifestyles, Building, Transport, Industry, Agriculture and Energy supply modules, while afforestation is tackled in the Forestry module. This report focuses on detailing the modelling assumptions, data sets and lever settings allowing the CCUS module to simulate the following 3 sub-technologies:

- Carbon capture (CC): capturing waste carbon dioxide from large point sources, such as a coal power plant, a cement factory or a bio-energy power plant;
- Carbon utilization (CCU): making use of the captured carbon to produce fuels. In this case, CO2 serves as a necessary raw material for production of e.g. synthetic natural gas; The hydrogen needed for production of hydrocarbons is delivered from the storage module from excess electricity and renewable sources;
- Carbon sequestration (CCS): transporting the captured carbon to sequestration sites, and deposing it for preventing release into the atmosphere, typically in an underground geological formation. In this module, both onshore sequestration and offshore sequestration are analysed in a country-level granularity. The carbon flow from CC to CCS is illustrated in the Figure 1.

In terms of geographic location, CC takes place in carbon intensive power and industry plants, and these locations will serve as ideal starting points for CCU sites; while CCS is typically on "remote" sites demanding transportation infrastructure, such as pipelines. According to [1], pipelines serve as the main workhorse in CO2 logistics due to economic consideration. Therefore, the carbon transportation in this module involves uniquely the pipelines.

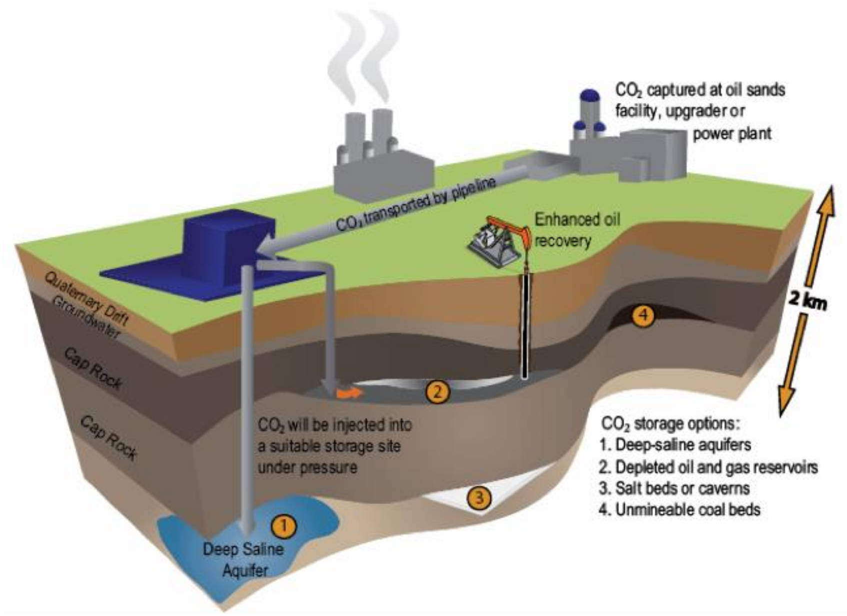

Figure 1 Carbon flow from CC to CCS [2]

This documentation is organised in the following way: chapter 1 introduces the CCUS modelling depth and scientific contributions; chapter 2 describes the calculation logic and the interaction with other modules; chapter 3 explains the lever definition and ambitious levels, followed by chapter 4 denoting a list of data used in the model and illustrating their use in the CCUS module; this is followed by an uncertainty analysis discussing both exogenous and endogenous factors. At last, the achievements and innovation needs derived during the work on the module are discussed in chapter 5.

1 Questions addressed by the module

1.1 Modelling depth

The CCUS module explores the role of carbon capture utilization and sequestration in the societal transition towards 2050. The model behind the CCUS module interacts with energy supply and manufacturing, and has explicit or implicit impact on other modules, such as fuel (distribution) and climate. Table 1 gives an overview of the main questions addressed by the module.

Table 1 Questions addressed

Theme	Questions		How is it addressed?
What are the types of impacts taken into account in the model?	Emissions	What is the potential for direct emissions CC?	The potential for CC in Industry and Energy supply is assessed for several CC technologies
		What is the potential for CCS?	The potential for CCS in different types of reservoirs is assessed for each country
	Fuel, Energy	What is the energy consumption of CC technologies?	An energy penalty is applied in the Industry and Energy supply modules when a CC technology is implemented
	Resources	What is the potential of CCU technologies?	CCU contributes to the production of synthetic natural gas (SNG) serving as a substitute of natural gas resource
	Economy	What is the cost of CCUS technologies?	The CAPEX and OPEX of each technology are implemented
What are the impacts of CCUS on the other sectors?	Energy demand		The energy penalty to install CC technologies increase the energy demand of Industry and Energy supply. CCU requires H2 to convert the CO2 into SNG.
	Climate		CCUS contributes to decreasing GHG emissions in Industry and Energy supply
	Energy supply		The production of SNG from CCU decreases the need for natural gas
What are the impacts of other sectors on CCUS?	Power		The electricity mix influences the potential for CC, and in turn CCS and CCU
	Industry		The industrial production and energy mix used influences the potential for CC, and in turn CCS and CCU

1.2 Scientific contribution

The scientific contribution and difference of the CCUS module in EUCalc compared to other public models/calculation tools are presented in Table 2. The difference refers to the model scope, granularity/ resolution, calculation method, data quality, inter sector interactions and geographic interactions.

Table 2 Scientific contribution.

Model	Description	Contribution of EUCalc CCUS module
IEA	The IEA has published several reports on the matter: on CC [2007] [3], CCS in industrial applications [2011] [4], a CCS technology roadmap [2013] [5], and a CCS accelerating future deployment manifest [2016] [6]	The EUCalc CCUS module refers to some of the cost and efficiency IEA data and uses the highly aggregated numbers for validation. However, the granularity provided by EUCalc CCUS is much higher in terms of specific application areas for CCUS technologies and their potential.
Global Calculator [1]	The Global Calculator focuses on CCS from ambient air (through biochar, direct air capture, ocean fertilization, etc., including 5 technologies)	Due to the high cost and energy penalty of direct air capture, EUCalc CCUS does not include CC from ambient air but focuses on CCUS from concentrated point sources including energy intensive industrial plants and the electricity sector, including bio-energy carbon capture (BECC)
Times/ Markal	Several TIMES/Markal based CCS (carbon capture and sequestration) models/analyses have been published, e.g. [7]	EUCalc CCUS module has a higher spatial granularity, covering EU28 countries and Switzerland.
PRIMES[2]	CCS is considered based on three types (pre-/post-combustion and oxyfuel) in the power sector. The model represents transport and sequestration of CO2 through reduced-form inter-temporal cost-supply curves for each country.	EUCalc CCUS considers a higher granularity for carbon capture technologies. Sequestration is considered based on actual estimated country-specific potentials. Additionally, CO2 utilization is also covered.
BREF literature	The BREF documents cover CC in their "large combustion plants"-issue [12–14][8]. There is no specific BREF documentation for CCUS itself.	EUCalc CCUS includes CCS and CCU technologies

1 Link to global calculator (greenhouse gas removal, GGR)
2 Link to PRIMES documentation.

2 Calculation logic and scope of the module

2.1 Overall logic

The aim of the CCUS module is to provide trajectories until 2050 for each European country (EU28 + Switzerland) for the following variables:

- Potential of carbon capture by technology [Mt] and associated energy penalty [TWh] in industry and energy supply sectors;
- Potential of carbon sequestration underground by technology with country-specific granularity [Mt];
- Potential of synthetic fuel production from carbon utilization with country-specific granularity [Mt];
- Implementation cost of CCUS technologies [M€].

The emissions and the captured emissions transferred to the CCUS module are calculated by other modules, e.g. the captured emissions associated with the electricity production are calculated by the energy supply module and captured emissions associated with industry are calculated by the industry module. The CCUS module provides the specific cost and energy penalty data of carbon capture technologies deployable in the industry and power modules.

The CCUS module covers the state-of-the-art technologies for carbon capture (CC), sequestration (CCS), and utilization (CCU) in the industry and power sectors which are among the top three emitters of anthropogenic GHG emissions in Europe. This is illustrated in Figure 2, where industry and energy supply account for 41% of total anthropogenic GHG. The remaining GHG contributors apart from industry and power supply are not considered, due to either their relatively small emissions or the difficulty to apply current CCUS technologies in an economically- acceptable way, such as the transport sector despite its large contribution to GHG.

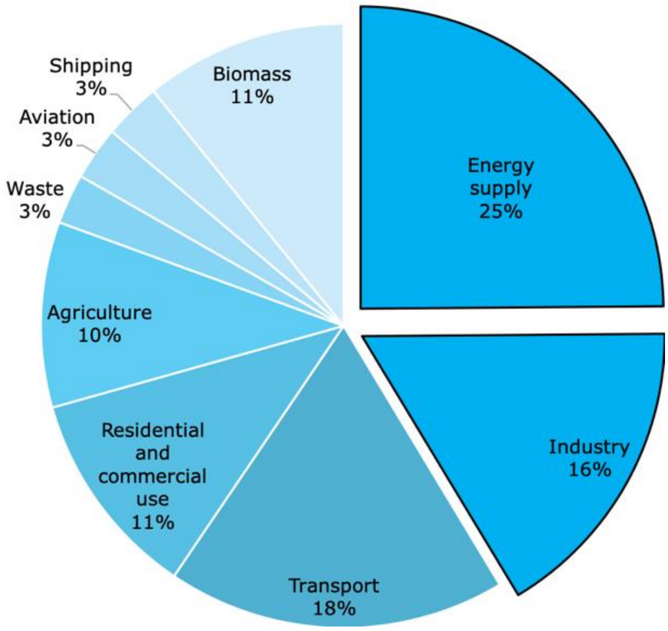

Figure 2 Anthropogenic GHG emissions by sector in the EU-28 [9].

To identify the CCUS technologies, data was collected from various sources (as indicated in the respective tables) for quantifying the efficiency, energy penalty and resulting cost for each technology. In spite of its development in recent years, CCUS is still applied in small scale in Europe and in the whole world, resulting in a lack of historical data, e.g. the annual data for the CO2-eq sequestrated and used by CCUS technologies. As a consequence, this data was assumed to be zero.

According to the Global CCS Institute & Parsons Brinckerhoff [10], the market for CO2 utilization is relatively small, and future markets for CO2 will have to map and prioritize points of CO2 emission with utilization opportunities, advocating for tailor-made and local solutions. This is addressed in this work in two ways:

- Firstly, by using country-specific data for the overall sequestration potential in the respective geographic region;
- Secondly by defining a lever (lever_ccus) which allows the user to control carbon utilization solutions against the standard practice of capturing and sequestrating carbon. The lever_ccus is defined as the ratio of carbon utilization over the overall captured emission in IPS in the horizon 2050.

2.2 Scope definition

The extensive list of GHG from the industrial and power sectors including BECC, the technologies and the fuel products taken into account in the CCUS module are represented in the Figure 3.

In this module, carbon capture in transport is not considered due to limited space and prohibitive specific cost for applying CC technologies. Decarbonisation is addressed through other measures in the transport module of EUCalc (e.g. electric mobility and bio-fuels, as discussed in the respective documentation).

Flue gas properties (CO2 partial pressure and concentration in the flue gases) of the various technologies and sub-processes of the power and industrial sector were taken into account and specific carbon capture technologies were suggested. Within the scope of the underlying module, the respective data (i.e. efficiencies & energy penalty of carbon capture technologies) have been collected and analysed, but the implementation is conducted in the industry and energy supply modules in order to avoid internal calculation loops.

The CCUS module receives the captured carbon (expressed as Mt CO2-eq. /y/country/sector) from the industry and power sectors, among which BECC is highlighted since it creates negative emission in the perspective of Life Cycle Assessment (LCA), as indicated explicitly by the IPCC. In the CCUS module, BECC stems from both industry (such as paper/pulp making) and power sector (such as bio-power production). CCUS then quantifies the flow of carbon for sequestration or for utilization according to the lever definition. It accounts for the CCS potential of each country, its transportation cost and further the corresponding utilization and sequestration energy penalty and cost, as well as the CCU fuel output. The overall scope of CCUS module is indicated in Figure 3.

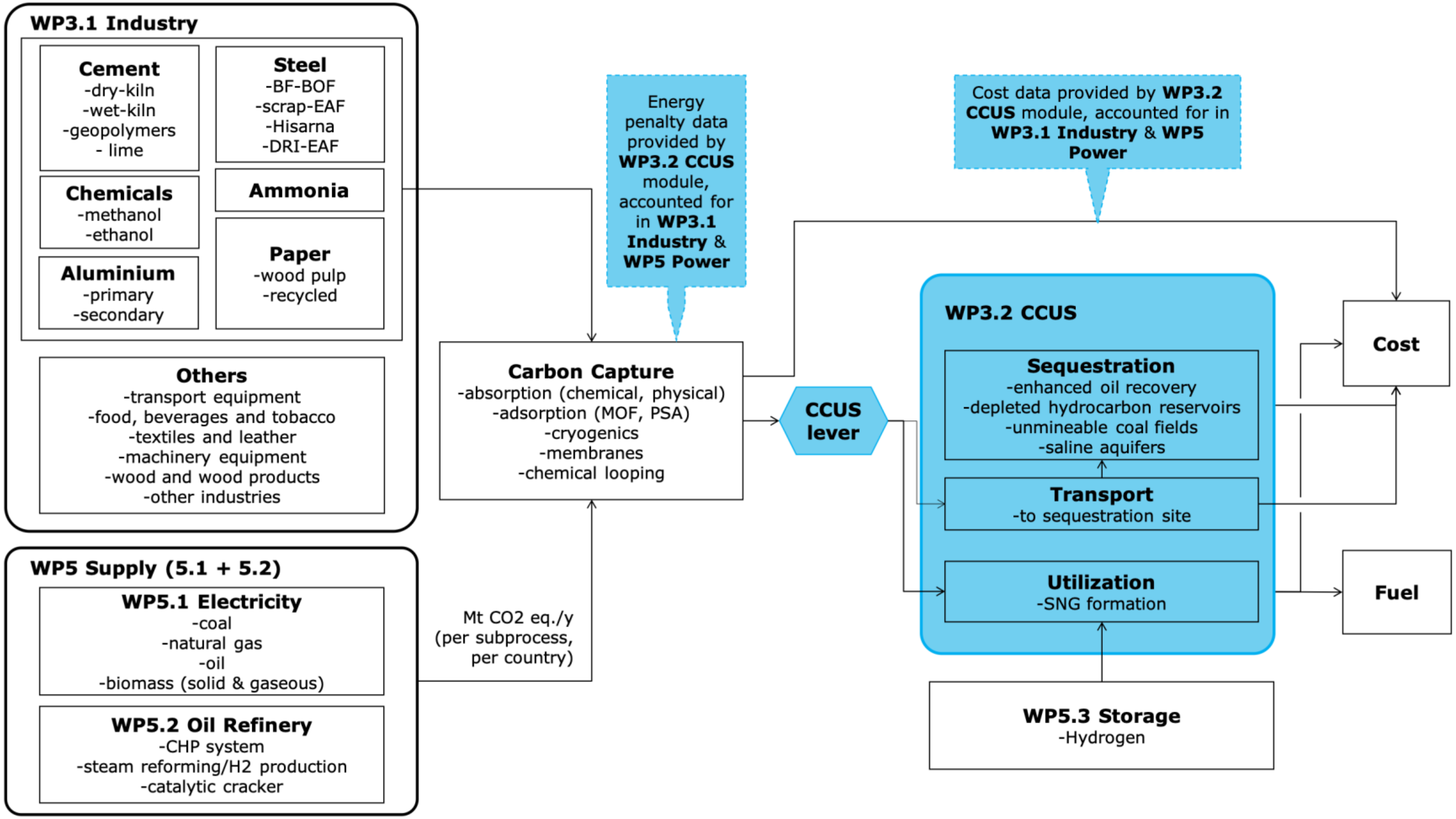

Figure 3 Scope of the CCUS module.

2.2.1 Carbon capture

Carbon capture is usually categorized into three different groups which are depicted in Figure 4: *pre-combustion*, *post-combustion*, and *oxyfuel combustion*, classifying where gas separation is applied: on the combustion flue gases (post-combustion), after gasification/steam reforming and a water-gas-shift reaction on the hydrogen rich stream (pre-combustion), or before combustion separating oxygen from air (oxyfuel combustion).

However, as illustrated in Figure 5, the underlying technologies which may be applied for gas separation within each of the three categories can overlap. Therefore, both the category name and technology name are used in the following sections.

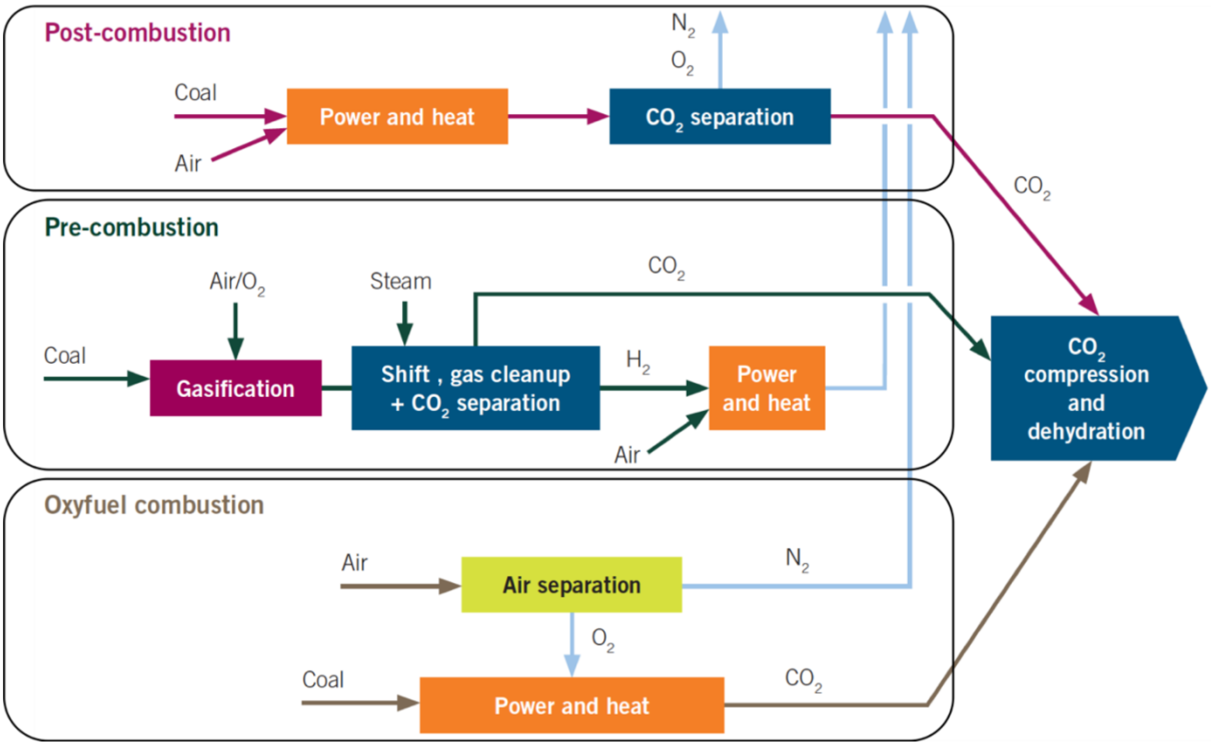

Figure 4 Carbon capture categories, reprinted and modified from [10].

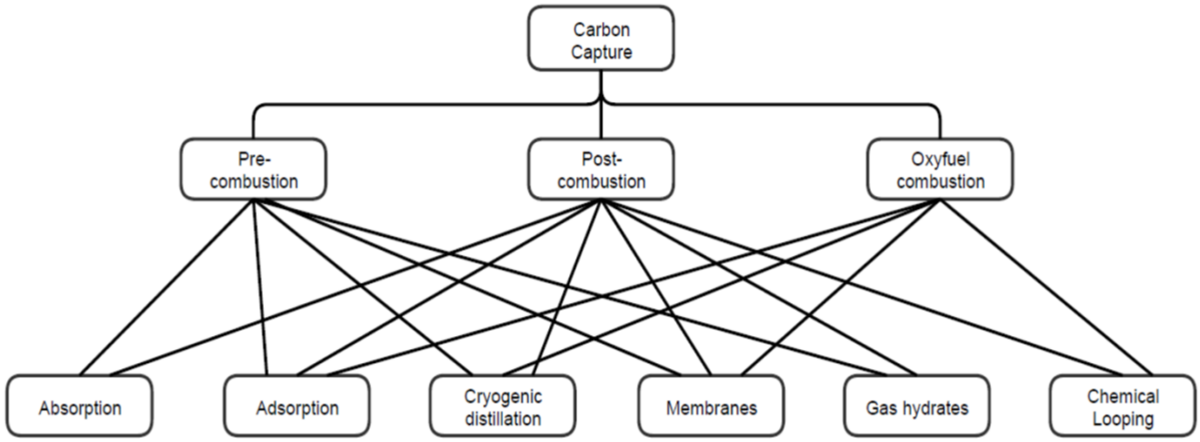

Figure 5 Carbon capture classification and technologies [11].

The carbon capture technologies considered in EUCalc are presented below:

- absorption (chemical, physical)
- adsorption (metal organic frameworks (MOF), pressure swing adsorption (PSA))
- cryogenic distillation
- membranes
- chemical looping

Among the 5 technologies listed above, the chemical/physical absorption is considered commercially acceptable while the others are under development. Currently, chemical solvent scrubbing is the most widely used method for capturing CO2 from low pressure and low concentration flue gases. The majority of chemical solvents are amine-based and the most widely used is Monoethanolamine (MEA) [12], though amines of superior performance are increasingly used [13]. Since CO2 is an acid gas, alkaline solvents like MEA will form chemical bonds with it. This property can be used to absorb CO2 from a flue gas stream. Once the CO2 has been absorbed from the flue gas, energy can be applied to the absorbent to release the CO2 for utilization/storage and in the meantime regenerating the solvent for reuse in the process. In physical solvent absorption, CO2 from a gas stream is weakly absorbed by the solvent under conditions of high pressure and released when the pressure is reduced to allow solvent regeneration. The most commonly used physical solvent is Selexol consisting of dimethylethers of polyethylene glycol. Alternatives include cold methanol (Rectisol), N-methyl-2-pyrolidone (Purisol) and propylene carbonate (Fluor solvent). [12]

Carbon capture from ambient air (DAC) was not considered in the CCUS module for two reasons: 1) their prohibitive cost and heavy energy penalty, which 2) creates a computational loop issue with the power supply module.

2.2.2 Carbon sequestration

Carbon sequestration (CCS) usually follows the capture of CO2 to prevent carbon from release to the atmosphere. Currently, carbon sequestration is preferred to carbon utilization by industry since it is less energy intensive and relatively simple and cheap to operate. Geological carbon sequestration, such as enhanced oil recovery (EOR) and saline aquifers, is currently the most prevailing way to store CO2 compared to other storage methods such as mineral storage and CO2 liquefaction or solidification. Technology readiness levels (TRL) of up tp 9 can be achieved [13].

The technologies for carbon sequestration considered in the CCUS module have been carefully selected based on studies estimating their respective potentials in the European context [14–16] both on- and off-shore. Those technologies include:

- Enhanced Oil Recovery (EOR)
- Depleted hydrocarbon Reservoirs
- Non-mineable Coal Seams
- Saline aquifers

The Figure 6 and Figure 7 depict the geographical distribution of CCS fields across Europe. Country-specific geological information for EU28 and Switzerland on carbon sequestration is available in the Appendix.

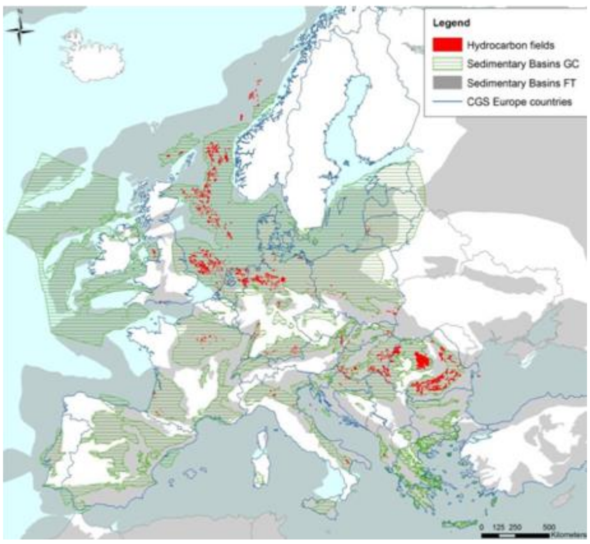

Figure 6 Extent of sedimentary basins (in grey: Fugro Tellus (FT), 2008; in shaded green: GeoCapacity (GC), 2009) and potential hydrocarbon fields for CO2 storage in Europe (GeoCapacity, 2009). [16]

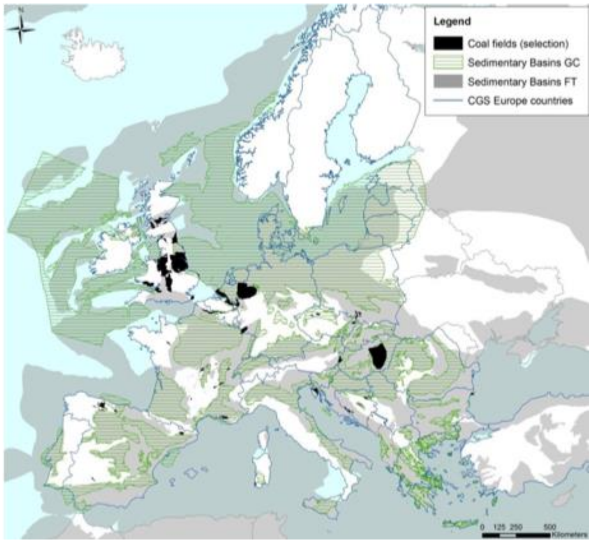

Figure 7 Extent of sedimentary basins (in grey: Fugro Tellus (FT), 2008; in shaded green: GeoCapacity (GC), 2009) and potential coal fields for CO2 storage in Europe (GeoCapacity, 2009). [16]

The corresponding potential for each CCS technology in EU28+Switzerland is listed in Table 8 (Section 4.1.2), with adapted data collected from a broad range of literature references. The CCS technology mix is determined in line with the share that each technology holds among the total CCS potential in a country-specific granularity. It is assumed that only CCU is available for the countries without CCS geological feasibility, considering both onshore and offshore potentials. In the long term, a wide European CO2 distribution network could solve the geographical constraints, but since such a system is not in place and neither planned, the focus was on a country-wide granularity to determine individual potentials.

2.2.3 Carbon utilization

Carbon utilization (CCU) is an alternative to carbon sequestration. Carbon dioxide, as a source of carbon, has the potential to contribute to the production of fuels, typically synthetic natural gas (SNG, or synthetic methane) and other chemical products, such as propylene, ethylene, polyvinyl chloride etc. For these routes a maximum TRL of 6 can be reached [13]. CCU to the chemical products are not considered in the model since: 1) re-using CO2 for chemicals will always be limited since the total mass output of the chemical industry is 14-20 times [17] smaller than the current output from energy industry [18]; 2) looping problems arise when giving back the chemical products into the industry module. By consequence, CCU in this module refers only to the generation of fuel. Two criteria for a feasible and promising method for carbon dioxide conversion to useful fuels include the following:

- the fuel from the conversion should be clean, safe and usable by industry and power sectors;
- the conversion process should be economic and environmentally friendly.

Among all potential fuels, SNG has an extensive application in industry, power and transport, which could also be easily converted to other fuels if needed. As a result, SNG is chosen as the only output of CCU. Furthermore, SNG production by CCU is becoming increasingly promising in the context of a massive penetration of renewables, particularly for alleviating the intermittency brought about by PV and wind: CCU could serve as an effective long-term storage method by making use of excessive electricity to synthetize natural gas, known as Power-to-Gas (PtG), allowing shifting the electricity production peak to deficit periods, and thus contributing to the frequency/voltage balance in power grids, particularly essential with the development of smart girds. In PtG process, water is split into oxygen and hydrogen by electrolysis, which is then fed with captured CO2 from carbon intensive fields for SNG generation. [19]
As a substitute of natural gas (NG), SNG can simply be stored in the existing gas grids (see Appendix A.1 Countries' average CO2 transport distance and Ref. [20]) and transported to various applications, whenever and wherever needed, e.g. for the generation of electricity/heat, or as a fuel for vehicles or ships [21].

Therefore, CCU combined with PtG facilitates the coupling of different energy sectors. This concept is illustrated in the Figure 8. In terms of thermodynamic and structural properties, the module does not distinguish SNG and NG hereafter. In order to highlight the development potential of CCU, a lever is defined and explained in section 3 Description of levers and ambition levels.

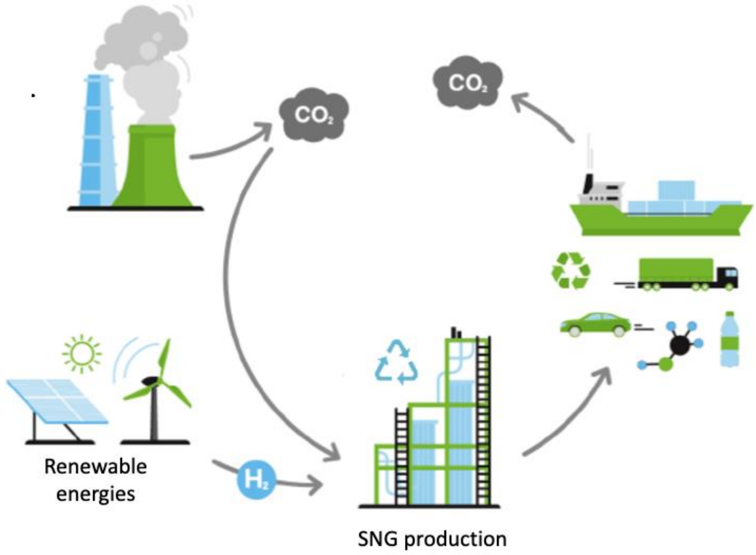

Figure 8: Carbon utilization schematics (adapted from [22])

2.2.4 Difference between CCS and CCU

In general, CCU calls for more investment and is much more energy-demanding than CCS; But the energy consumption in CCU could be partly transferred to produce fuels, allowing its application in long-term storage. Compared with CCU, the energy penalty of CCS is negligible.

Despite the common contribution that both CCS and CCU make for carbon mitigation, the impacts they exert could be categorized into:

- Direct impact: CCS serves as a direct carbon sink, implying sequestration of the captured CO2 underground that is not supposed to be released back into atmosphere within hundreds/thousands of years; The TRL is high;
- Indirect impact: The used CO2 can eventually be emitted into atmosphere, e.g. by combustion of SNG in a vehicle. Instead of directly reducing anthropogenic CO2 emission, CCU contributes to the decarbonization in an indirect approach by compensating part of fossil fuel demands. The TRL is lower than CCS.

2.2.5 LCA analysis of carbon flow chain

2.2.5.1 Carbon flow chain and biogenic carbon capture

Life-cycle assessment or life cycle assessment (LCA, also known as life-cycle analysis) is a methodology for assessing environmental impacts associated with all the stages of the life-cycle of a product, process, or service [23]. In the context of CCUS, we distinguish two major carbon sources: biogenic and non-biogenic as illustrated in Figure 9: biogenic (left) and non-biogenic (right) carbon capture. Usually the emissions from a biogenic carbon source are assumed as net zero due to the CO2 absorption by biomass via photosynthesis. This excludes the CO2 emissions from mining and transportation processes which are already accounted for in corresponding modules in EUCalc. As a result, the BECC technologies will lead to negative emission. For non-biogenic carbon, the emission is calculated by the emission factors in specific power and industry sectors.

Note: Biogenic carbon capture is considered in EUCalc from bio-energy production in the industry and power sectors using biomass or biogas as fuels. What is not considered in EUCalc is biogenic carbon capture through the use of biomass (e.g. timber) in the building and construction sectors.

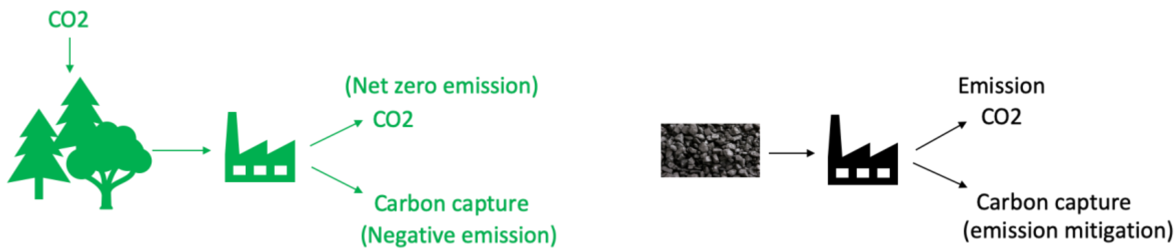

Figure 9: biogenic (left) and non-biogenic (right) carbon capture

This practice allows to define scenarios in agreement with the definition in the SAPEA report [24], which proposed three options for CCU: one for positive emission with all captured carbon from fossils going to be used and released to atmosphere again; the second refers to negative emission by BECC; the third is a combination of the two with net zero emission. It highlighted that the presence of CCU in a technology chain is not sufficient to lead to an O-economy (circular economy) without participation of biomass that enables biogenic carbon recycling and energy production as well, which is regarded as a key plus compared to DAC as purely energy sink. Ref. [24] mentioned for evaluating the impact of a new technology solution, following steps should be made :

1. the whole technology chain to which the new technology solution belongs should be described and identified;

2. such description should include the source of C-free resources, the source of CO2 and of other chemicals needed, the product generated and its typical tLIFE;

3. accordingly, material and energy balances around the system boundaries defined should be calculated, using the best estimates from the literature;

4. additionally, infrastructure needed and land use (for biomass growth and DAC) associated to the scheme of interest should be estimated from the literature;

5. the current and projected scale of the new technology solution should be estimated and the relevant assumptions articulated.

2.2.5.2 Realisation in the Calculator

As presented in the Industry and Power documentation, EUCalc tracks the carbon sources and defines CC potentials in technology and sector specific levels, and explores various pathways for carbon sinks, including circular utilization of both biogenic and non-biogenic carbon sources. Thus, points 1 and 5 are addressed. Since the carbon utilization is modelled using renewable excessive e-H2 from WP5, point 2 is covered. Point 3 on corresponding material and energy penalty is considered and quantified in Table 7 Carbon capture technologies for the power and energy-intensive industrial sector.. As to the infrastructure in point 4, in CCUS, the pipeline infrastructure for carbon transportation is modelled and corresponding cost are estimated by identifying the distance between major carbon sinks and sources within country-specific level for onshore and offshore storage. DAC is yet not modelled due to calculation loop issue. In terms of the biomass growth, it is explained in the documentation 4.1.

Figure 10 depicts the carbon flows of three example pathways: (a) non-biogenic, (b) biogenic, and (c) mixed. The fraction of carbon capture in the industry and power sectors and split between carbon utilization and sequestration are discussed in the respective sector documentations and later in this report. The three routes discussed here are just exemplary. In route (a), out of the 100 units of non-biogenic carbon supplied to the industry and power modules, 40 units of carbon are directly emitted to the atmosphere, while 60 units of carbon are captured. Out of these 60 units, 35 units are sequestrated and 25 are utilized. The utilized carbon can actually be re-supplied to the industry and power sector thus decreasing the net fuel requirement, but not impacting the total emissions of 40 units.

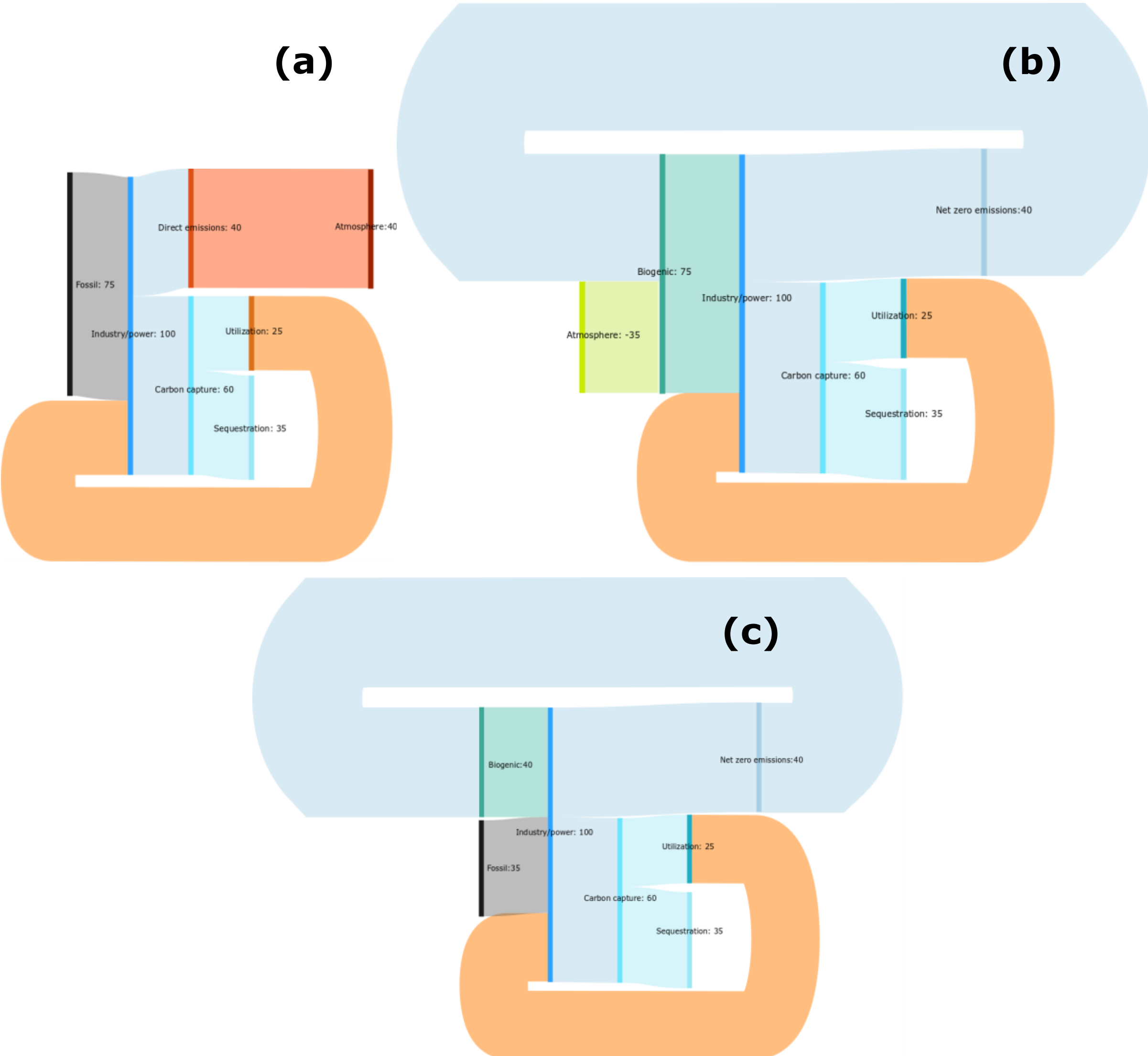

Figure 10: non-biogenic (a), biogenic (b), and (mixed) net-zero emissions (c) carbon capture utilization and sequestration routes

In route (b), the main fraction of the industry and power requirements (apart from the re-utilized carbon) is supplied by biogenic carbon (75 units). Out of the 100 units of consumed carbon, 60 are captured (and sequestrated or utilized) and 40 are emitted to the environment. Thus, net negative emissions of -35 units result from this configuration. In route (c), the biogenic carbon is reduced to 40 units of input, while a total of 40 units are *not* captured which leads to net zero emissions to the environment.

The modelling approach in EUCalc realises this behaviour in such a way that the industry and power modules report the CO2 emissions from non-biogenic carbon sources emitted to the environment (non-biogenic CO2 emitted) and the biogenic carbon sources captured (biogenic CO2 captured); the non-captured biogenic emission is regarded as net zero. The two quantities are separately displayed on the pathway explorer and lead to a correct net balance. This is illustrated below for the three example pathways (with 60% carbon capture):

(a) Non-biogenic CO2 emitted: 100*(1-0.6) = 40 units, Biogenic CO2 captured: 0 units, Net emissions: 40-0 = 40 units
(b) Non-biogenic CO2 emitted: 25*(1-0.6) = 10 units, Biogenic CO2 captured: -75*0.6 = -45 units, Net emissions: 10 – 45 = -35 units
(c) Non-biogenic CO2 emitted: 60*(1-0.6) = 24 units, Biogenic CO2 captured: -40*0.6 = -24 units, Net emissions: 24-24 = 0 units

2.3 Interactions with other modules

2.3.1 Inputs

2.3.1.1 *Industry*

The CCUS module receives from the manufacturing and production module (here referred to as industry) the amount of GHG captured (in the form of CO2-eq, unit: Mt) in each European country every five year until 2050. The industrial sector constitutes one of the major sources of anthropogenic emission of GHG with about 16% of total emissions, as shown in Figure 2. The main energy intensive industrial processes are enlisted below:

- Cement: dry-kiln, wet-kiln, lime and geopolymers
- Chemicals: methanol, ethanol
- Aluminium: primary, secondary
- Paper: wood pulp and recycled
- Steel: BF-BOF, scrap-EAF, HIsarna, DRI-EAF
- Ammonia

Other industrial processes are modelled in the industry sub-module but they do not produce emissions apart from their energy requirements (e.g. electricity) which are accounted for in the power module. Those industrial sectors are hence not discussed in this document.

2.3.1.2 Electricity and Refinery

Similar to the industry, the electricity and oil refinery modules (summarised here with energy supply or power module) provide to the CCUS module the amount of GHG captured (in the form of CO2-eq, unit: Mt) in each European country every year until 2050 with step 5 years. In the power module, the main sources for carbon capture are:

- coal-fired,
- oil-fired,
- and gas-fired power plants
- bio-energy plants (gaseous and solid biomass), referred to as BECC
- as well as oil refineries

For each source listed above, more detailed technological divisions are implemented: for instance, CC technologies are distinguished into integrated gasification combined cycle (IGCC) and non-IGCC for coal-fired plants. Detailed information is available in the Table 7 (see section 4.1.1).

2.3.1.3 Storage

Apart from captured CO2, hydrogen takes part in the SNG production. In EUCalc, the H2 for P2G is fed by the module Storage, which uses available excess electricity in the system to generate H2.

2.3.2 Outputs

The CCUS module calculates the amount of captured CO2 used [Mt/y] for CCS (including CO2 transport) and CCU in country-specific and technology-specific granularities, as well as the corresponding CAPEX and OPEX.

In order to explicitly illustrate the share of CCS among the maximal potential of sequestration in a country, the accumulated CCS [Mt] over years is calculated as an output to the pathway explorer.

2.3.2.1 Minerals

The outputs from carbon utilization are able to take the same role as common fuels, resulting in a decrease of fuel demand. The output fuels in the CCUS module refers to:

- SNG (unit: TWh): Synthetic natural gas

The output SNG will be integrated into the module Storage (WP5.3) to be designated for further utilization, e.g. in gas power plant, transport etc.

2.3.2.2 TPE

The transition pathway explorer (TPE) is the graphical interface of EUCalc. The captured carbon by subsector as well as the carbon sequestrated or utilized by the various technologies and their costs are sent to the TPE.

2.3.3 Summary

Figure 11 depicts the lever (described in more detail below), inputs and outputs of the CCUS module as described in the previous sections.

Accuracy: 100%	100%	100%	100%	100%	100%	100%	100%	100%	
LEVERS	INPUT						OUTPUT		
Naming convention	1.3 Technology	3.1a Industry	3.1b Industry Ammonia	5.1 Electricity	5.2 Oil Refinery	5.3 Storage	0.2 Pathway Explorer	4.2 Minerals	6.4 Employment
lever_ccus	Country	Years	Years	Years	Years	Years	Years	Years	Years
	capex_ccu_ccus_transport[MEUR]	ind_CO2-emissions-CC_cement_dry-kiln[Mt]	amm_CO2-emissions-CC_ammonia_amm-tech[Mt]	elc_stored-CO2_gas-ff-natural[Mt]	ref_stored_CO2[Mt]	sto_hydrogen[TWh]	ind_CO2-emissions-CC_cement_dry-kiln[Mt]	ccu_ccus_gas-ff-natural[Mt]	ccu_capex_methane-formation[MEUR]
	capex_ccu_ccus_enhanced-oil-recovery[EUR/(t/y)]	ind_CO2-emissions-CC_aluminium_sec[Mt]	Country	elc_stored-CO2_liquid-ff-oil[Mt]	Country	Country	ind_CO2-emissions-CC_aluminium_sec[Mt]	Country	ccu_capex_enhanced-oil-recovery[MEUR]
	capex_ccu_ccus_depleted-oil-gas-reservoirs[EUR/(t/y)]	ind_CO2-emissions-CC_steel_hydrog-DRI[Mt]		elc_stored-CO2_solid-ff-coal[Mt]			ind_CO2-emissions-CC_steel_hydrog-DRI[Mt]		ccu_capex_depleted-oil-gas-reservoirs[M
	capex_ccu_ccus_unmineable-coal-seams[EUR/(t/y)]	ind_CO2-emissions-CC_steel_hisarna[Mt]		elc_stored-CO2_solid-bio_mass[Mt]			ind_CO2-emissions-CC_steel_hisarna[Mt]		ccu_capex_unmineable-coal-seams[MEU
	capex_ccu_ccus_deep-saline-formation[EUR/(t/y)]	ind_CO2-emissions-CC_steel_BF-BOF[Mt]		elc_stored-CO2_gas-bio_gas[Mt]			ind_CO2-emissions-CC_steel_BF-BOF[Mt]		ccu_capex_saline-aquifers[MEUR]
	capex_ccu_ccus_methane-formation[EUR/(t/y)]	ind_CO2-emissions-CC_cement_wet-kiln[Mt]		elc_stored-CO2_total[Mt]			ind_CO2-emissions-CC_cement_wet-kiln[Mt]		ccu_capex_transport[MEUR]
	opex_ccu_ccus_transport[EUR/t]	ind_CO2-emissions-CC_lime_lime[Mt]		Country			ind_CO2-emissions-CC_lime_lime[Mt]		Country
	opex_ccu_ccus_enhanced-oil-recovery[EUR/t]	ind_CO2-emissions-CC_chem_chem-tech[Mt]					ind_CO2-emissions-CC_chem_chem-tech[Mt]		
	opex_ccu_ccus_depleted-oil-gas-reservoirs[EUR/t]	ind_CO2-emissions-CC_steel_scrap-EAF[Mt]					ind_CO2-emissions-CC_steel_scrap-EAF[Mt]		
	opex_ccu_ccus_unmineable-coal-seams[EUR/t]	ind_CO2-emissions-CC_aluminium_prim[Mt]					ind_CO2-emissions-CC_aluminium_prim[Mt]		
	opex_ccu_ccus_deep-saline-formation[EUR/t]	ind_CO2-emissions-CC_paper_recycled[Mt]					ind_CO2-emissions-CC_paper_recycled[Mt]		
	opex_ccu_ccus_methane-formation[EUR/t]	ind_CO2-emissions-CC_cement_geopolym[Mt]					ind_CO2-emissions-CC_cement_geopolym[Mt]		
		ind_CO2-emissions-CC_paper_woodpulp[Mt]					ind_CO2-emissions-CC_paper_woodpulp[Mt]		
		Country					amm_CO2-emissions-CC_ammonia_amm-tech[Mt]		
							elc_stored-CO2_gas-ff-natural[Mt]		
							elc_stored-CO2_liquid-ff-oil[Mt]		
							elc_stored-CO2_solid-ff-coal[Mt]		
							elc_stored-CO2_solid-bio_mass[Mt]		
							elc_stored-CO2_gas-bio_gas[Mt]		
							ref_stored_CO2[Mt]		
							ccu_ccus_total-carbon-capture[Mt]		
							ccu_ccus_methane-formation[Mt]		
							ccu_ccus_enhanced-oil-recovery[Mt]		
							ccu_ccus_depleted-oil-gas-reservoirs[Mt]		
							ccu_ccus_unmineable-coal-seams[Mt]		
							ccu_ccus_saline-aquifers[Mt]		
							ccu_ccus_ccs-potential-occupation[%]		
							ccu_ccus_transport[Mt]		
							ccu_capex_methane-formation[MEUR]		
							ccu_capex_enhanced-oil-recovery[MEUR]		
							ccu_capex_depleted-oil-gas-reservoirs[MEUR]		
							ccu_capex_unmineable-coal-seams[MEUR]		
							ccu_capex_saline-aquifers[MEUR]		
							ccu_capex_transport[MEUR]		
							ccu_opex_transport[MEUR]		
							Country		

Figure 11 Levers, inputs, and outputs of the CCUS module.

2.4 Detailed calculation tree

The calculations in the CCUS module can be divided into 4 subsequent steps, which are shown in the Figure 12:

1. **Carbon capture**: the first step is to integrate the annual CO2 emissions captured from the industry and energy supply sectors by summing up all the captured carbon emissions [Mt CO2-eq] provided by the industry and energy supply sector (as presented in the Figure 3) from 2015 until 2050 (with 5 year steps).

2. **Carbon sequestration**: this step aims at calculating the carbon sequestrated and total cost for deploying CCS. The amount of captured carbon that will be sequestrated is determined directly from the lever_ccus in case the national potential of CCS is not saturated. Once the geological potential is surpassed, the excessive captured carbon will be treated by CCU. Then the total sequestration amount is disaggregated into different CCS technologies. CCS is associated with an efficiency factor [%], as well as a cost factor [EUR/tCO2/y]. All the three factors are assumed to be constant in time and geographical location (see section 4.1). Thereafter, the investment cost is derived. There are no fuel outputs in the CCS case. In addition, the energy penalty for CCS is negligible compared with CCU, and energy penalty factors for CCS technologies have been set to 0 by consequence. Furthermore, transport costs apply since the storage sites are located in remote areas usually far from large carbon point sources i.e. industrial clusters.

3. **Carbon utilization**: this step is responsible for estimating the annual total amount of CO2 allocated to CCU, more precisely by methanization in the sense that methane is highly demanded in the industry and transport sector, and it is able to be converted into other fuels. By multiplying the total carbon capture obtained in the step 1 with the share [%] determined by the lever_ccus, this quantity is derived. CCU is associated with an efficiency factor [%] and hydrogen demand [tH2/tCO2], as well as a cost factor [EUR/tCO2/y]. All the three factors are assumed to be constant in time and geographical location (see section 4.1). Based upon the amount of CO2 available for CCU, the amounts of the fuel product[3], the energy demand expressed as the amount of H2 needed, and the cost linked to this technology are deduced by multiplying the correspondent factors mentioned above. Transport costs are neglected, since, unlike CCS, CCU can be located close to large point sources.

4. **Aggregation**: this step aggregates all the fuel product, energy requirement and cost produced in the CCU and CCS, providing the total cost for a given amount of captured CO2 and sends them to the pathway explorer.

[3] The mass for each fuel product is calculated by mass conservation law of carbon element after having multiplied the efficiency factor.

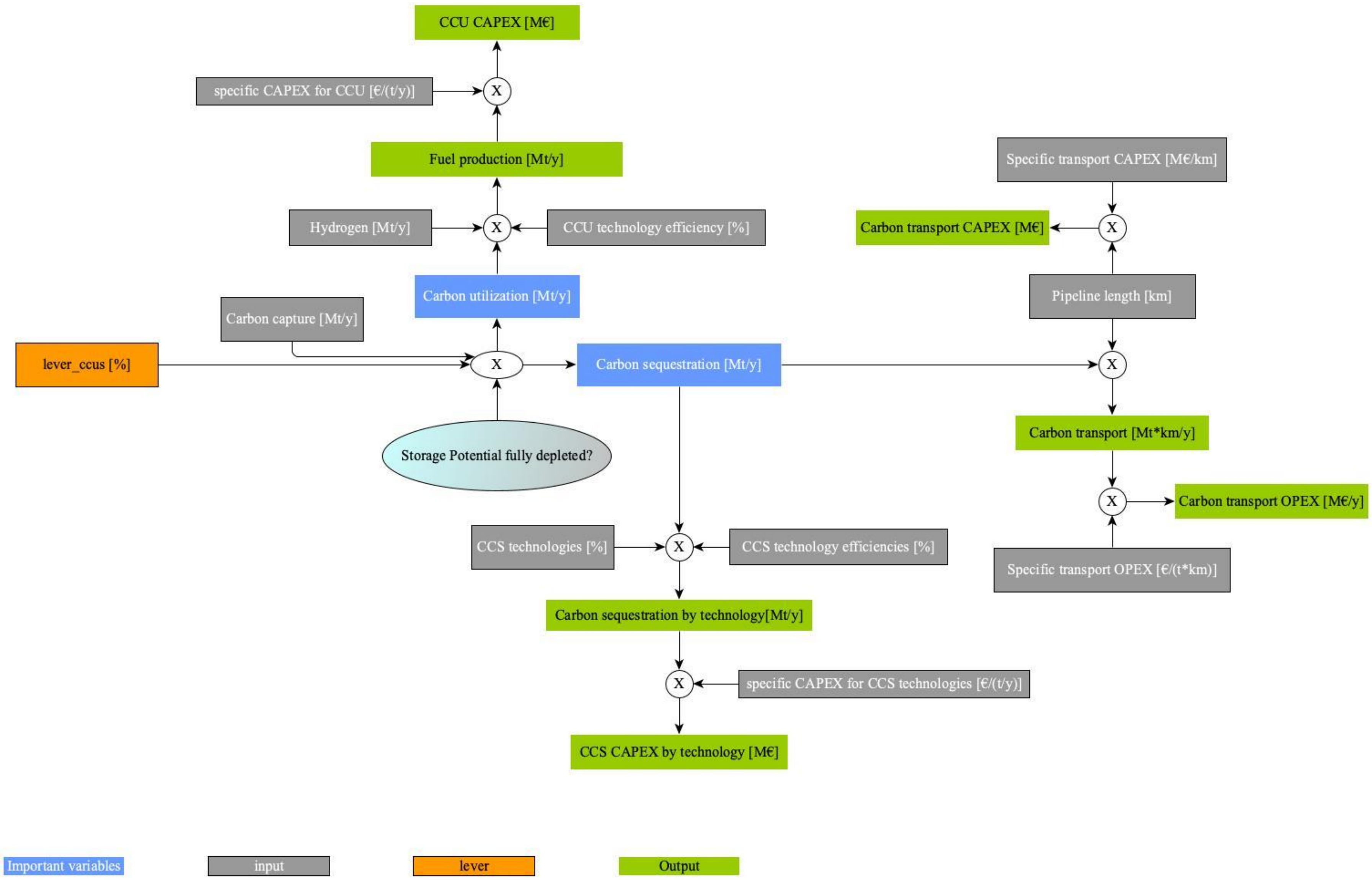

Figure 12 CCUS calculation tree.

3 Description of levers and ambition levels

3.1 Lever list and description

There are in total three levers concerning CCUS: two levers defined in industry and power modules respectively and one defined in this module. The two defined in industry and power control the amount of CO2 [%] that could be captured from industry and power respectively. It is highlighted that the lever levels vary in industry and power due to different capture difficulties and policies. Detailed information with regard to the two lever and their settings is available in the D3.1 and D5.1.

In this module, the lever named lever_ccus determines the strategy between utilization and storage of the captured carbon in the industry and energy supply modules. More precisely, the lever describes the percentage of CCU technologies with respect to the total captured carbon, assuming that:

$$Carbon\ capture = Carbon\ sequestration + Carbon\ utilization$$

Or in acronyms: CC = CCS + CCU

An increasing amount of fuels are expected as the CCUS lever value rises, while in the meantime the costs are estimated to be elevated due to the higher unit investment of CCU than CCS. Hence this lever plays a role for measuring the trade-off between investment, useful products and emission reductions (as discussed more in the subsequent section).

Table 3 summarizes the proposed lever. The calculation tree in Figure 12 shows where the lever is applied in the calculations.

Table 3 List of levers for CCUS module.

	Lever	Brief description
1.	CCUS [%]	= CCU/CC Percentage of CCU applied to the captured carbon dioxide.

3.2 Ambition levels

In EUCalc, the ambition level definition primarily aims at defining different levels of ambition for CO2-eq emission reductions. Since the CCUS levers defines the ratio of CCU over CC, this definition seems a little stretched since both technologies (CCU and CCS) technically contribute to reducing carbon emissions. CCU, however, also contributes to synthetic fuel generation by renewable resources which sheds light on alleviating intermittency of increasing PV and wind turbines from PtG; the fuels produced can then be recycled for use in industry, power plant and transport etc. Due to the benefit of PtG and the recycling effect, CCU is regarded as the most ambitious technology. Figure 13 shows the defined ambition levels for this lever and further indicates the accompanying effects. Along with increasing carbon emission reductions, higher political acceptance is expected together with higher capital expenses.

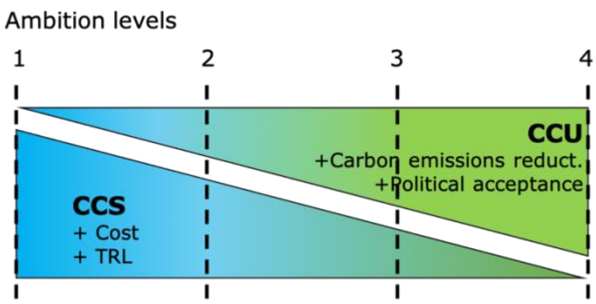

Figure 13 Ambition levels and influence of CCS and CCU.

Table 4 represents the lever ambition levels of the CCUS module and the mix of CCU technologies assumed within these levels. In the following, a detailed account and motivation for the defined lever positions and CCU technology mix is provided. The CCS mix is based on each country's respective potentials.

- **LEVEL 1: Business as usual**
  This level contains projections that are aligned and coherent with the observed trends.

  No access to historic trends of CCUS is available, since the technologies are relatively new and not yet widely implemented. However, as stated in section 2.2.2, from a cost and technology readiness level point of view carbon sequestration is preferred over utilization, and it represents lower carbon reductions compared to utilization.

  Therefore, for ambition level 1, 100% carbon sequestration is assumed in each country, as long as sequestration potential is available. The split within CCS technologies is given by the specific countries' potentials.
  In case the country's CCS potential has been fully exhausted (or is non-existent), CCU is applied.

- **LEVEL 2: Ambitious but achievable**
  This level is an intermediate scenario, more ambitious than business as usual but not reaching the full potential of available solutions.

  Similar to Level 1, mostly sequestration is suggested here, with 33% of utilization. The CCU contributes to the production of SNG.
- **LEVEL 3: Very ambitious but achievable**

This level is considered very ambitious but realistic, given the current technology evolutions and the best practices observed in some geographical areas.

Under the aegis of the lever, CCU dominates the CCS in the sense that increasing carbon products are expected. This lever consists in exploring the impact of largely but not complete deployment of carbon utilization in power and industry systems in the future.

- **LEVEL 4: Transformational breakthrough**
  This level is considered as transformational and requires additional breakthrough and efforts such as a very fast market uptake of deep measures, an extended deployment of infrastructures, major technological advances, or strong societal changes, etc.

  This lever corresponds to the full development of Decarbonization where the captured carbon is all converted to useful products for satisfying fuel demands in order to prevent further exploitation of fossil fuels. In this ambition level, the role of CCU as a carbon sink is fully exploited, and thus contributing to a benign cycle for low carbon society.

Table 4 Lever definition for CCUS module – same in each country.

	Name / Unit	1	2	3	4
lever	**CCUS [%] = CCU / CC**	0	33	66	100

4 Data

4.1 Constants list

The constant parameters stand for the parameters that are constant over years. Additionally, the constant parameters are lever-indifferent, meaning they are not affected by any lever.

4.1.1 Carbon capture (CC)

Table 7 shows the overall information of carbon capture technologies applied to the industry, electricity and oil refinery modules, including the correspondent TRL, efficiency, energy penalty (in terms of thermal and electrical energy), and specific cost (in terms of CAPEX and OPEX) for each technology. These data stem from a broad range of literature listed in the source column. Additional specifications, such as hypotheses and further explanations, are also presented in the table.

4.1.2 Carbon sequestration (CCS)

4.1.2.1 Countries' potentials

Each country's potential for carbon sequestration sites in the EU-28+Switzerland group was analysed and is reported in Table 8. Apart from the total sequestration potential (in Mt CO_2), also the average transport distance (in km) is reported as well as the estimated amount of newly built pipelines this requires (in percent of the transport distance). In Appendix A.1 Countries' average CO2 transport distance, the background for the latter two parameters is provided.

4.1.2.2 Transport costs

4.1.2.2.1 Capex

Since transportation grids are usually planned across countries and carried out by large international corporations [25], the capital expenses (CAPEX) for transport are assumed to be constant across Europe28 + Switzerland.

For the CAPEX, a cost per length of pipes is defined. From [25] (Figure 4.3), the following average data was retrieved: $param_{capex}$ [onshore] = 0.6 M€/km, $param_{capex}$ [offshore] = 0.8 M€/km.

The CAPEX of the transport equipment is then derived using the following equation.

$$CAPEX_{transport}[€] = distance[km] \times renovation\ rate\ [\%] \times param_{capex}[€/km]$$

where the renovation rate is expressed as % of newly built pipelines (see Table 8) for carbon transport.

4.1.2.2.2 Opex

The transport OPEX are presented in Table 5 derived from Ref. [10], cross-checked and verified with aid of Ref. [25].

Table 5 Transport opex for large-scale networks (20 Mt/yr), reprinted from [10].

Distance (km)	**0-180**	**181-500**	**501-750**	**751-1500**
Onshore pipe (€/t CO2)	1.5	3.7	5.3	n/a
Offshore pipe (€/t CO2)	3.4	6.0	8.2	16.3
Ship with liquefaction (€/t CO2)	11.1	12.2	13.2	16.1

4.1.2.3 Technology costs

A similar rational as for transport CAPEX, is used for technology CAPEX.

Table 6 displays various properties and sources used for defining the parameters of CCS. The capex found in literature is reported in euro per ton of carbon stored. Since EUCalc requires the capex per (annual) capacity, the values from literature were converted (see column *) using the assumption of 20 years of operation of the sequestration site. These values were backed up with data from Ref. [25] for two offshore storages, including compression equipment, storage preparation, drilling and well completion cost (Table 5.10 with 1-0.7 Mt CO2/y; 109-240 USD/(t/y)).

The energy penalty for CCS are assumed to be 0 since it is much less than (approximately 10% of) the CCU [26], in order to avoid loop problem in the model. The efficiency is defined as tons CO2 equivalent which are permanently sequestrated compared to the tons of CO2 captured.

Table 6 Constants list for CCS. (Assumption: 20 years of sequestration in one site)

Technology	**TRL [18]**	**Effi-ciency**	**Elec. penalty (KWh/tCO2-eq)**	**Capex [on/off shore] (€/tCO2-eq)**	**Capex [on/off shore] * (€/(tCO2-eq/y))**	**Source**
Enhanced Oil Recovery (EOR)	9	0.95	0	2.5	50	[25]
Depleted Oil and Gas Reservoirs (DOGR)	7	0.95	0	3 / 6	60 / 120	[10,25]
Unmineable Coal Seams (UCS)	9	0.95	0	4 / 10	80 / 200	[10,25]
Saline aquifers	9	0.95	0	5 / 14	100 / 280	[10,25]

Table 7 Carbon capture technologies for the power and energy-intensive industrial sector.

			TRL	Efficiency [%]		Energy penalty[4]		Capex [€/(t/yr)]		O&M [%]		Source	Comment
				2015	2050	2015	2050	2015	2050				
Electricity Supply	Coal	IGCC	9	90		16%		90		0		[10,25,27]	Pre-combustion by chemical absorption with Selexol, O&M included in Capex
	Coal and Gas	Coal-fired plants and Gas-fired plants	7→6	90		32.5 %	17%	132	102	0		[25,27,30–32]	Post-combustion by chemical absorption with MEA (2015) → Post-combustion by adsorption PSA (2050, the capex is site-specific and holds a large range)
			7	90		32.5%		221		0		[33] [34]	Oxyfuel, O&M included in Capex → not recommended due to high costs
	Gas	NGCC	9	86.5		17%		194		0		[10,25,27]	Pre-combustion by chemical absorption with MEA, O&M included in CAPEX
Oil Refinery	Oil refinery	CHP system	7→6	85	87	41%	15%	203	256	8	2	[35]	Chemical absorption (2015)→ Oxyfuel (cryogenic) (2050)
		Steam-reforming & WGSR (for H2)	6	77		34%		160		5		[35]	Pre-combustion with membrane.
		Catalytic cracker	7	94		38%		160		12		[35]	Post combustion

[4] The units for energy penalty in power sector and industry are different: KWh_{el}/t or KWh_{th}/t for industry while % for power, representing an efficiency drop in power sector if CC is applied. Advantage of the unit desegregation is to avoid loop problem in power sector.

Industry	Steel	BF-BOF (air blown / top-gas recycling)	6→4	-		960 kWh_{th}/t 140 kWh_{el}/t	230 kWh_{el}/t	85	90	5	[35]	Chemical absorption (2015) → Membrane absorption (2050)
		scrap-EAF	7	99		0	0	0		0	[36]	"The EAF process requires large amounts of electricity to melt the scrap steel but has no other sources of CO_2 emissions."
		HIsarna	7	95		0	0	0		0	[35]	The input carbon is fully oxidized within the smelter so that CO_2 removal is unnecessary.
		DRI-EAF	7	-		90 kWh_{el}/t		1			[37]	
	Cement	dry-kiln / wet-kiln / geopolymers	6→3	95	65	275 kWh_{el}/t	150 kWh_{el}/t	120	50	5	[35]	Assumption: 0.85 tons of CO_2/ton of clinker [38]. Oxyfuel on the entire plant (2015) → calcium looping (2050).
	Chemicals	Methanol, DME, FT fuels production	9→6	90		120 kWh_{el}/t	90 kWh_{el}/t	160	145	5	[32,39,40]	Physical absorption (2015) → PSA (2050) Assumption: 8760 h/yr, 20 yr lifetime
		Ethanol production	-	-	-	0		0		0	[41]	The fermentation process releases almost pure CO_2 which does not require specific sequestration equipment.
	Paper	Wood pulp	7	62		1160 kWh_{th}/t		250		5	[42,43]	New: cogeneration system. Therefore, difficult to assess the capex. Assumption: 5% maintenance.

		Recycled	-						Assume that the only CO2 emissions stem from the energy supply of the system (heat + power). Therefore, see above in the power sector.
	Ammonia	Steam-reforming (for H2)	9	95	120 kWh_{el}/t	160	5	[32,40]	Assumption: Hydrogen production process: same as methanol production with chemical absorption

Table 8 Countries' CCS potential, average transport distance, and percentage of newly built pipelines for transport.

Country	Total storage potential (Mt)			Transport properties		Source	Comments
	Saline aquifiers	Depleted oil & gas reservoir	Unmineable coal seams	Distance (km)	Newly built (%)		
Austria	0	465	0	-	-	[44]	The Austrian government decided to ban the industrial use of geological CO2 storage in Austria except for scientific purposes until 2018.
Belgium	199	0	0	-	-	[15,45]	Sequestration capacity is neglected because numbers are not promising, and government is not in favour of it.
Bulgaria	2100	3	17	75	50%	[15]	50% of point large sources are in 150 km distance to storage locations.
Croatia	2710	189	0	20/ 150[5]*	100%	[15]	20% is offshore transport to an offshore aquifer.
Cyprus	0	0	0	-	-	[46]	According to [46], published by the ministry of agriculture of Cyprus, CCS is only foreseen in the near future by afforestation.
Czech Republic	766	32.7	54	60	50%	[15]	Mainly aquifers. Potential for EOR in hydrocarbon and coal fields.
Denmark	2553	203	0	24	100%	[15]	30% of sources at 80km distance. Conservative estimates calculated assuming that the aquifer systems surrounding and connected to the reservoir formations in the trap structures are closed (confined) aquifers.
Estonia	0	0	0	725	100%	[15]	Ref. [15] suggests the use of Latvian underground aquifers which generates this travelling distance. However, this was not considered in the CCUS module.
Finland	0	0	0	-	-	[47]	No suitable geologic formations exist to sequestrate CO2.
France	7922	770	0	140	50%	[15]	20% of point large sources are in 700 km distance to storage locations

[5] *Offshore storage.

Germany	10’000/ 2900*	2180	0	0/500*	50%	[15]	90% onshore storage, assumption: 10'000 Mt (50% of total potential onshore)
Greece	184	70	0	-	-	[15]	Sequestration does not seem feasible comparing emissions with potential.
Hungary	140	389	87	100	100%	[15]	
Ireland	2840*	1505*	0	100	100%	[48]	All sinks are off-shore. Average distance to most close shore.
Italy	4669	1810	71	340	50%	[15]	70% of sources at 100km distance, 30% at 900km distance.
Latvia	404	0	0	100	50%	[15]	Biggest distance Riga to Saldus, storage in aquifers.
Lithuania	30	7	0	-	-	[15]	Mainly aquifers, practical potential is estimated at zero.
Luxembourg	0	0	0	-	-	[15]	As things are now there is no CO2 storage potential in Luxemburg.
Malta	0	0	0	-	-	-	Due to insufficient literature no storage capacity assumed.
Netherlands	340	1700	300	50	50%	[15]	Without significant financial incentives storage in coal is probably not economically feasible.
Poland	1761	764.3	415	50	50%	[15]	Low transport distance, since most sources are within close proximity to storage locations.
Portugal	331/ 2211*	0	0	50/20*	50%	[49]	Mainly offshore storage.
Romania	7500	1500	0	50	50%	[15]	Only one-point source away from storage locations.
Slovakia	1716	(133.5)	0	107.5	50%	[15]	Mainly aquifers
Slovenia	92	2	0	75	100%	[15]	“No economic factors, potential conflict of space use, public acceptance or safety conditions have been considered in this project.”
Spain	14000	34	145	250	50%	[15]	
Sweden	100	0	0	-	-	[15]	Available data is limited, for instance on cap rock properties, to actually do any reliable estimates
Switzerland	2680	0	0	100	100%	[50]	
UK	7100	7300	0	40	50%	[15]	20% of point sources 200km distance to storage locations.

4.1.3 Carbon utilization (CCU)

Table 9 displays various properties and sources used for defining the parameters of CCU. The efficiency is defined as tons of synthetic methane which is generated divided by the tons of CO_2 fed to the CCU plant.

In industrial practice, the energy penalty is commonly compensated by taking the output fuels as energy resource. By doing this, the efficiency is modified in Table 9 marked with an asterisk (*). It is then straightforward to calculate the absolute energy penalty of CCU by taking the difference of the two efficiencies. The electricity requirement for H_2 production is not considered in this module since it is computed in the Storage module. In order to keep consistent to industrial practices and avoid calculation loops, the efficiency in the model follows the industrial practice and is set to the modified value.

Table 9 Constants list for CCU.

Technology	TRL [13]	Effi-ciency	Input (t in/ t CO_2)	Prim. penalty (kWh/t prod)	Efficiency*	Capex (€/(t CO_2/yr))	Sources
Methane formation	6	0.345	0.182 H_2	1010[6]	0.320	310	[51][52][7]

4.2 Uncertainty

Uncertainty calculations and analysis are not in the scope of EUCalc and hence were not quantitatively considered within the CCUS module. In the following section, however, the main sources for uncertainty within the module are discussed. The uncertainty of the application of CCUS technologies stems in principle from two aspects: exogenous uncertainty and endogenous uncertainty. The exogenous uncertainty refers to the uncertainty beyond control, such as the change of relevant politics; in contrast, endogenous uncertainty is within the system, such as the improvement of CCUS technology efficiencies. More precisely, the uncertainty in CCUS involves:

- Politics: few evidences foresee the development of CCUS technologies without political support, due to their high investment and energy penalty. The political decisions, in particular the emission mitigation objectives, play an essential role stimulating further deployment of CCUS technologies. Besides, in some countries, CCS is temporarily forbidden by law, for instance in Austria (until 2018), in the Czech Republic (until 2020), in Latvia (until 2013) and in Sweden (until January 2013), principally due to geological stability consideration. Therefore, the uncertainty from political decisions is determinant to the future of CCUS.

[6] Energy requirement for hydrogen production is not accounted, which is available in WP5.3 Storage.
[7] LHV (Lower heating value) of methane: 50 MJ/kg [47], reaction temperature 400 °C, heat required for feed preheating, exothermic reaction, capacity factor 1.

- Economics: CCUS is sensitive to economic factors, such as the price of fuels. For the moment, the costs for CCUS technologies vary in a large range according to different sites [25]. In addition, the uncertainty on the evolution of renewable energies, especially the cost reduction of renewables, competes to some extent with the development of CCUS technologies in the sense that a higher penetration of renewables implies less carbon sources and decreasing demand for CCUS technologies.
- Technology development: the uncertainty brought about by the technology development of CCUS is mainly interpreted as the improvement of the technological efficiencies, probably leading to a drop of CCUS investment cost that is prohibitive for the moment. But the uncertainty source is less significant compared with the above two aspects unless big technological breakthrough is achieved. This can however not be accounted for in our data.
- Other uncertainty: GDP development, population evolution and change of lifestyle etc. All these uncertainties will directly or indirectly influence the future material and energy demands, and thus have an effect on the development of CCUS.

5 Conclusions and outlook

5.1 Achievements

The CCUS module provides a detailed analysis of the CCUS process by breaking down the carbon flow from capture (CC), sequestration (CCS) and utilization (CCU). The carbon is captured in industry and power subsectors (including biogenic carbon capture) by CC technologies in a process-specific granularity in agreement with technological and economic feasibilities. The CCUS module provides the data as well as the decision support for carbon capture in the other two subsectors. Once captured, the carbon can be either sequestrated or utilized depending on a lever position and on the potential left for sequestration. This CCS potential for EU28 and Switzerland is analysed country-specific according to the geological and geographical limitations, taking into account onshore and offshore carbon storage potential and including analysis of carbon transportation from sources to sinks (e.g. existing pipelines). This increased granularity allows to analyse the bottlenecks in carbon transport and sequestration on the European map. If not sequestrated, the carbon is used and transformed into synthetic natural gas, providing a "carbon-neutral" alternative to natural gas since the electricity used for the transformation process (to produce hydrogen) comes from excess renewable electricity.

5.2 Further research and innovation needs

Currently, the carbon utilization (CCU) route modelled in the CCUS module is production of synthetic natural gas which is then transferred to the minerals module. Four alternatives (including different fuels and chemicals) were originally considered and aborted due to calculation chain issues. The sequential resolution approach of the calculator does not allow to create "loops" which would send products of the CCUS module to modules upstream of the calculation chain (e.g. the transport, industry, power). This limits the flexibility of the CCUS modelling approach, which could only partially be overcome by demand-driven modelling, as is explained in the following paragraph.

The current logic of the CCUS is that the carbon available from the industry and power sectors for capture drives the use and sequestration processes. As an alternative, CCS and CCUS could be modelled independently. While CCS could still be computed thanks to a CC lever (controlling the amount of carbon captured in industry and power), CCU could be determined by the demand of synthetic fuels (also called "e-fuels"). This would allow to deepen the policy narratives for instance in the transport sector where e-fuels could be an alternative to electrification. However, this improvement requires several adjustments of the model. First, direct air capture technologies – currently left out due to their prohibitive cost and heavy energy penalty, which creates a computational loop issue with the power supply module – should be introduced in the model. Second, the conversion road "renewable electricity to hydrogen to e-fuels" must be better represented in the power supply sector, which also entails a better integration of the CCUS and energy production modules, thereby moving the CCUS module upstream of the calculation chain and making it a "core" module. Indeed, the focus of the CCUS module would move from a mean to limit/decrease the GHG emissions towards a way to produce alternative e-fuels in the context of an increasing penetration of renewables.

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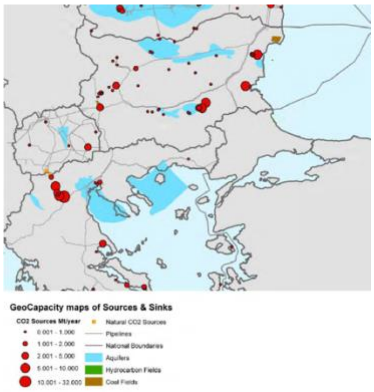
Appendix A

A.1 Countries' average CO2 transport distance

Table 10 provides the graphs based on which the average transport distance was derived. To that end, an analysis of the point sources and their distance to the next sequestration site was carried out. The average distance was then determined by weighing the distances with the size of the respective point sources. In order to identify the requirement for newly built pipelines (50, 75, 100%), a rough investigation of the available methane pipeline network was carried out: If a dense network was available, the fraction was set to 50%, while a sparse or non-existent network requires 100% newly built pipelines.

Table 10 Countries' average transport distance from point sources to sequestration sites.

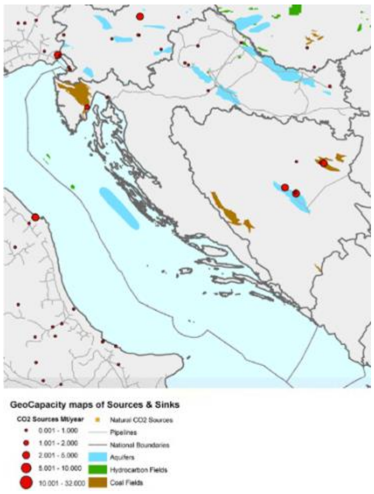
Bulgaria [15]



Distance: 75 km

50% of point large sources are in 150 km distance to storage locations.

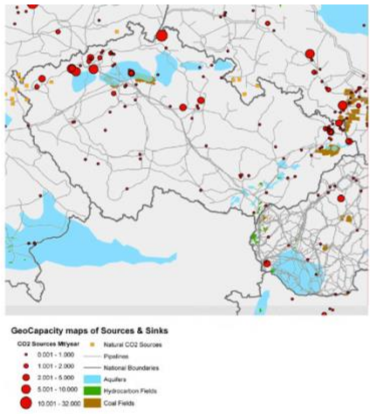
Croatia [15]



Distance: 20/ 150* km

20% is offshore transport to an offshore aquifer.

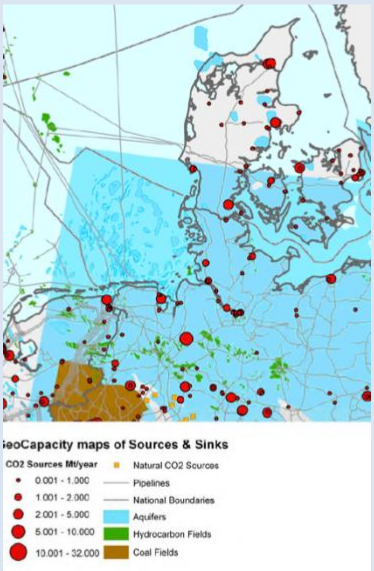
Czech Republic [15]



Distance: 60 km

Mainly aquifers.

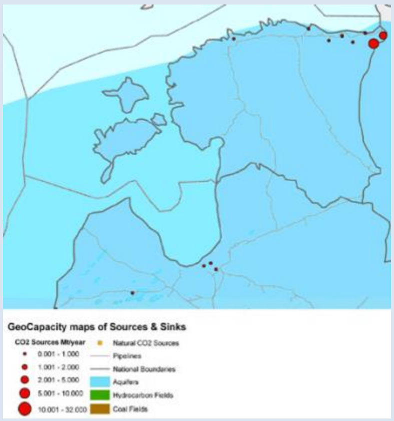
Denmark [15]



Distance: 24 km

30% of sources at 80km distance.

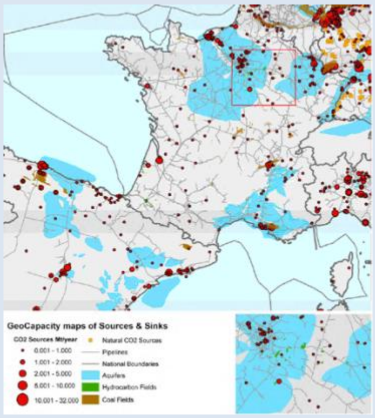
Estonia [15]



Distance: 725 km

Ref. [15] suggests the use of Latvian underground aquifers which generates this travelling distance.

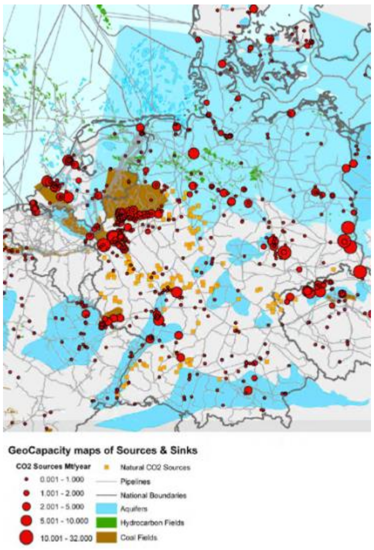
France [15]



Distance: 140 km

20% of point large sources are in 700 km distance to storage locations

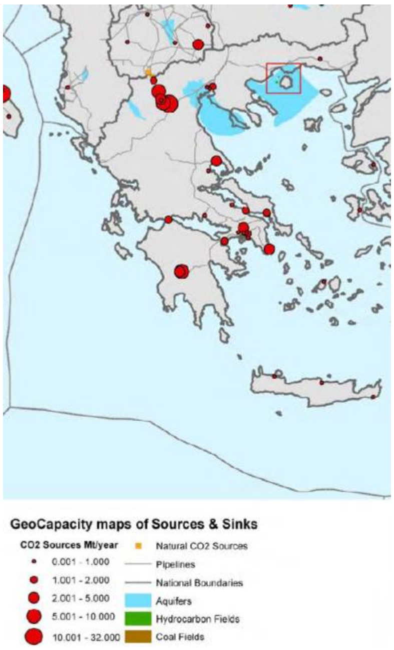
Germany [15]



Distance: 0/500* km

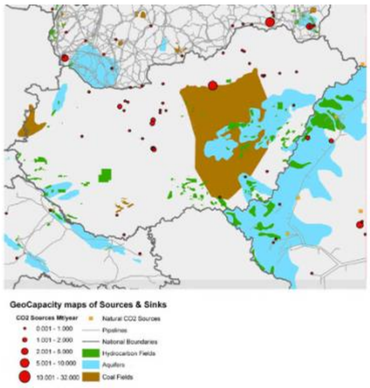
90% onshore storage, assumption: 10'000 Mt (50% of total potential onshore)

Greece [15]



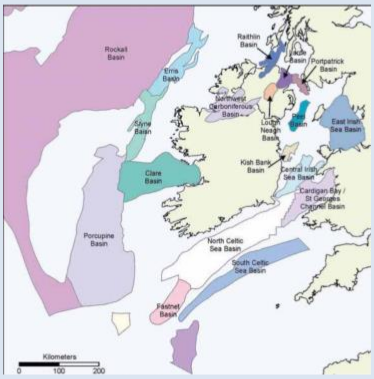
Distance: 250 km

Hungary [15]



Distance: 100 km

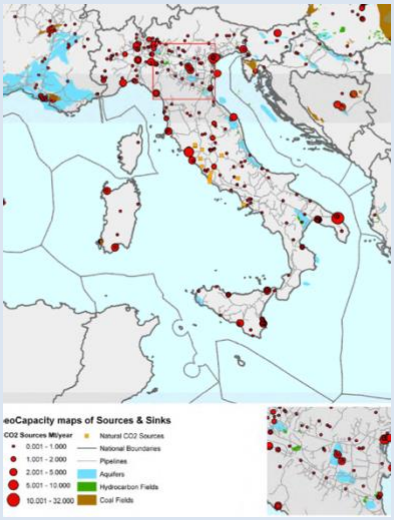
Ireland [53]



Distance: 100 km

All sinks off-shore.
Average distance to most close shore.

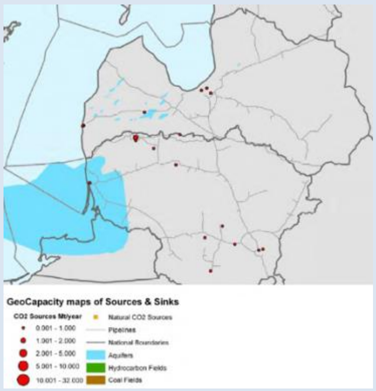
Italy [15]



Distance: 340 km

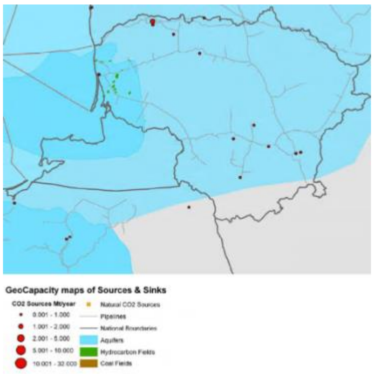
70% of sources at 100km distance, 30% at 900km distance.

Latvia [15]



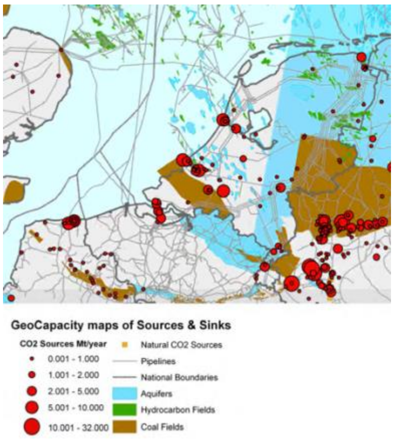
Distance: 100 km

Lithuania [15]



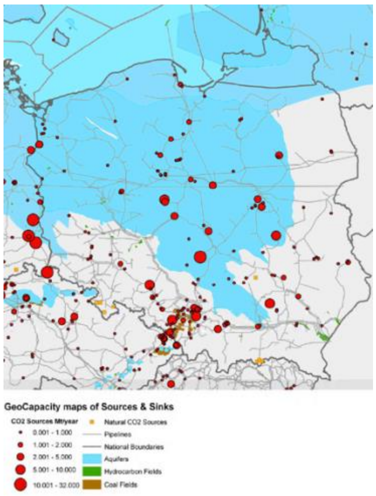
Distance: 252 km

Netherlands [15]



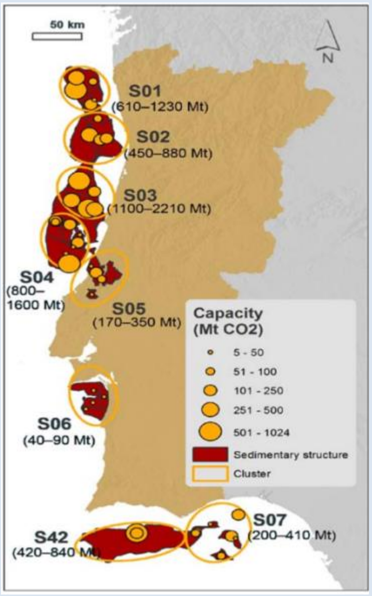
Distance: 50 km

Poland [15]



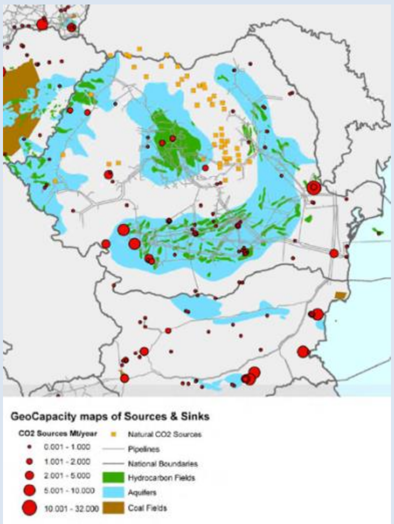
Distance: 50 km

Portugal [54]



Distance: 50 km

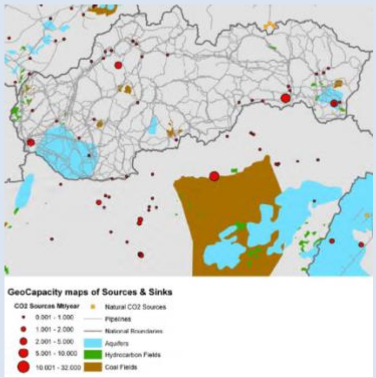
Romania [15]



Distance: 50 km

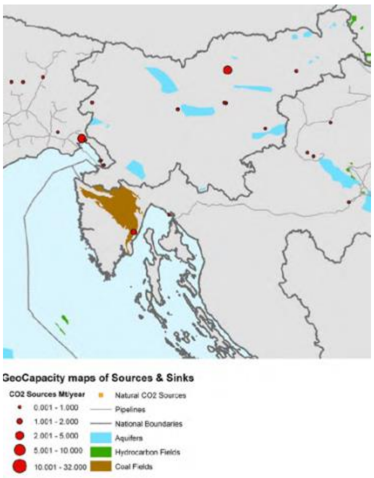
Only one-point source away from storage locations.

Slovakia [15]



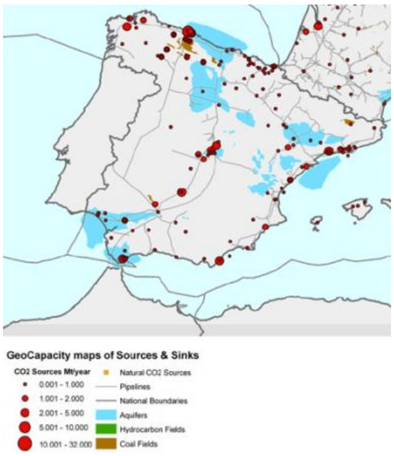
Distance: 75 km

Slovenia [15]



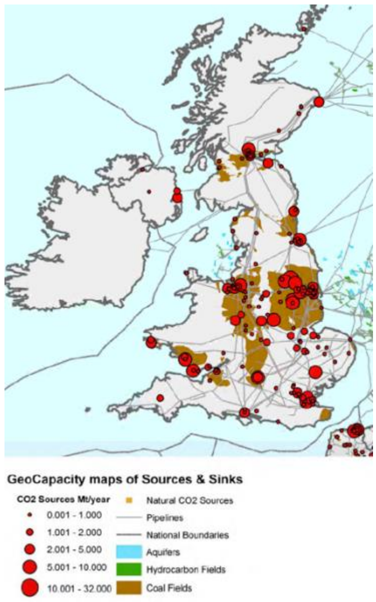
Distance: 75 km

Spain [15]



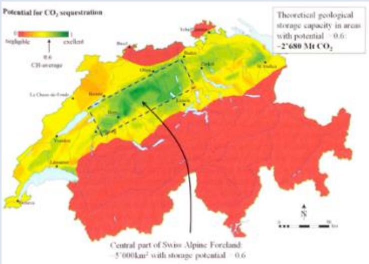
Distance: 250 km

UK [15]



Distance: 40 km

Switzerland [55]



Distance: 100 km